Uncovering Computational Primitives that Endow Neural Networks with their Information Processing Abilities

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Which computational primitives endow animal brains with their information-processing abilities, abilities that far exceed those of even the best modern computers? Answering this question would drastically change every facet of the society we live in, allowing the design of computers that are able to analyze satellite images and other intelligence data, recognize human faces, drive cars in urban centers, and help solve other national and global security problems.

Since the work of Emil du Bois-Reymond in 1848 and a series of discoveries by Santiago Ramón y Cajal (Nobel Prize in Physiology, 1906), it has been known that animal brains derive their powers from networks of interacting neurons of different types, which communicate with each other using stereotyped impulses, called action potentials or spikes. However, most experiments, going back to E. D. Adrian and Yngve Zotterman (1926) [1], seemed to suggest that the precise times of occurrence of these spikes matter little, and only the number of spikes over long time intervals (up to 100 ms or more) is used by neurons to encode their messages. This result has influenced the design of artificial neural networks, which, starting with the Perceptron [2], has neglected precise spike timing in favor of what has become known as the rate coding hypothesis [3].

However, such artificial neural networks have largely failed to deliver human-like cognitive performance. It has been suggested that one of the reasons behind this failure is the neglect of precise spike timing. A series of experiments by different scientists, summarized in [2], has shown that timing down to about 2 ms may be important for neuronal communication in visual information processing, supporting the argument. However, the duration of a single spike and the minimum distance between two successive spikes in real

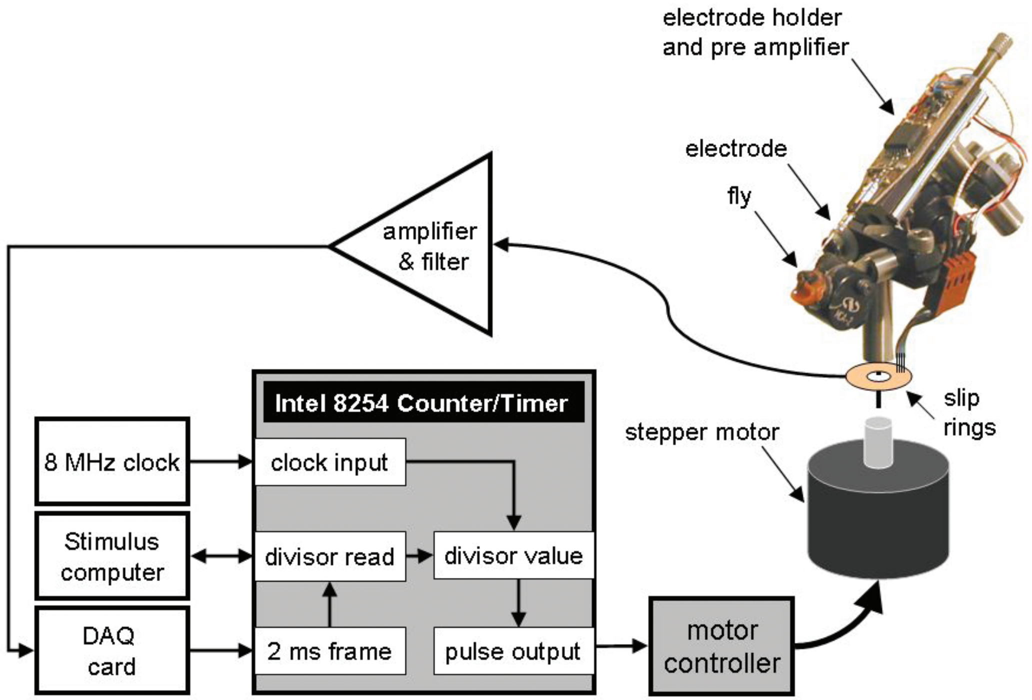

Fig. 1. A schematic of the experimental setup: a fly was immobilized with wax, its body in a plastic tube, with its head protruding. Through a small hole in the back of the head an electrode was inserted to record extracellular potentials from a specific neuron (called H1), a wide-field neuron sensitive to horizontal motion. This signal was amplified, fed through a slip-ring system to a second-stage amplifier and filter, and recorded by a data acquisition card. The signals were recorded in response to rotation of the whole setup around the vertical axis on a stepper motor. The angular velocity signal supplied by the motor was, in its turn, extracted from movies of flight behavior of real free-flying flies.

neurons is smaller than that. Could it be that animals use the spike timing to even higher precision, but the experiments have failed to see this usage?

In a 2008 article [4] the LANL-led team has explored the possibility that, when put in a natural environment (compared with earlier experiments done in a laboratory) with rich, dynamic, interesting stimuli, animals use spike timing with a precision down to a fraction of a millisecond. We used microelectrodes to record from the motion-sensitive neurons in the visual system of a common blowfly. To ensure that the fly's experiences were close to those in free flight, we immobilized the animal in an elaborate turntable-like mechanism, which was rotated to mimic the fly's natural acrobatic flight and was placed outdoors in the fly's natural environment (see Fig. 1).

We viewed the recording from the visual neuron as one would view a digital communication stream. We have explored how much information, in bits, is available in this stream when the position of each spike is known to a different accuracy. Data analysis for this experiment was even more difficult than the experiment itself: it took six years and required development of conceptually new statistical tools. When all the dust settled, we found that precise spike timing is important down to a resolution of 0.2-0.3 ms, an order of magnitude more precise than previous estimates in the literature (see Fig. 2). That is, neurons communicating with each other use precise spike timing to encode their messages, and this precision can be seen by observing that the information content of a spike train is higher if spike positions are known to a higher precision.

Such temporal accuracy is very far from Adrian's rate-coding theory, and it re-examines fundamental assumptions that became the basis of computational neuroscience and neuromimetic approaches to artificial intelligence. It is now clear that next-generation neural networks must consider precise spike timing as the mode of communication between their neurons as a very important computational primitive. Correspondingly, a new LANL Directed Research project

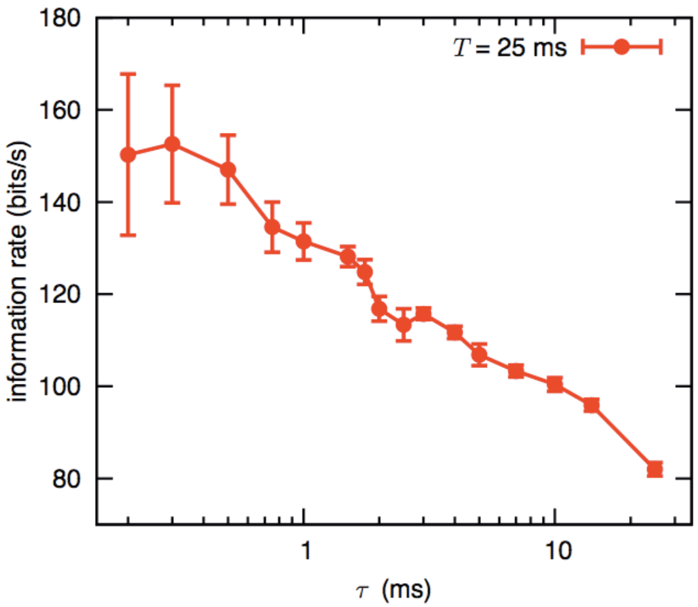

Fig. 2. The information content of the spike train as a function of time resolution t. The information is measured in "words" of duration of 25 ms, which corresponds to the fly's behavioral time scale. We plot this as a rate, in bits per second. Notice that the rate increases as the accuracy of spike-timing resolution increases.

started in FY09 will do just that, aiming at building the world-leading neuromimetic visual data processing platform based, in part, on proper incorporation of spiking into neuronal communications.

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[1] E.D. Adrian, Y. Zotterman, *J. Physiol.* (London) (1926).
[2] F. Rosenblatt, *Cornell Aeronautical Laboratory, Psychological Review* **65**(6), 386-408 (1958).
[3] F. Rieke et al., *Spikes: Exploring the neural code.* MIT Press (1997).
[4] I. Nemenman et al., *PLoS Comput Biol* **4**(3), e1000025 (2008).

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